

A method for determining look-angle stability parameters for VSAT control systems installed on ships with a non-orthogonal axis system

Ho Si Duong¹, Nguyen Trong Khuyen^{1*}, Nguyen Thi Le Quyen²

¹Control, Automation in Production and Improvement of Technology Institute, Academy of Military Science and Technology, 89 Ly Nam De, Hoan Kiem, Hanoi, Vietnam;

²Nghe An University of Economics, 51 Ly Tu Trong, Vinh city, Nghe An, Vietnam.

*Corresponding author: nguyentk126@gmail.com

Received 08 Aug. 2024; Revised 26 Nov. 2024; Accepted 03 Jan. 2025; Published 25 Feb. 2025.

DOI: <https://doi.org/10.54939/1859-1043.j.mst.101.2025.47-55>

ABSTRACT

The VSAT communication depends on many factors, such as signal strength, receiver sensitivity, and environmental interference factors. To ensure optimal signal quality, the VSAT antenna must remain properly aligned and polarized toward the satellite. For the VSAT system installed on the shipboard, the disturbances from waves, wind, and current significantly disrupt the antenna's ability to maintain a stable orientation toward the satellite target. To enhance structural efficiency, motion precision, and stiffness, some shipboard VSAT systems, such as the ORSAT AL7103 and AL7107, incorporate designs with motion axes that are not perpendicular. The article introduces a method for calculating look angle stability parameters for this type of VSAT system, including azimuth and elevation angles, rotation control angles, and the ship's attitude angles. Some experiment and simulation results support the theoretical analysis of the proposed method.

Keywords: Look angle stability; Polarization skew; Satellite tracking; Satellite communication.

1. INTRODUCTION

VSAT communication has been widely exploited all over the world. This is a wireless communication method that uses geostationary satellites for connectivity. It enables communication in remote and extreme areas, such as oceans or forests. In the VSAT control system, determining the look angles of antennas, along with the control parameters required to achieve these angles, is essential for maintaining a stable connection to the satellite. In [1], the concept of look angles is defined, including elevation and azimuth angles. The elevation angle is measured upwards from the local horizontal plane at the earth station, while the azimuth angle is determined starting from true north, measured in an eastward direction to the projection of the satellite path onto the local horizontal plane. The control system for VSAT can use two axes to regulate elevation and azimuth angles [2]. However, this approach causes the problem of gimbal lock, which occurs when the elevation gimbal is at an angle of 90° above the horizon. At this point, azimuth gimbal motion has no effect on line of sight orientation. The control system with three axes can help to eliminate the gimbal lock. In a three-orthogonal axis antenna on a shipboard with an azimuth-level-elevation mount, at lower elevation angles, stabilization is mainly controlled through the azimuth and elevation axes. At higher elevation angles, it relies on the elevation and level axes. The upper assembly is mounted on a single mast connected to the azimuth gimbal. However, this configuration results in a lack of stiffness. A shipboard antenna with a three non-orthogonal axis design can offer increased stiffness without significantly compromising performance compared to other orthogonal designs [2]. In [3], the authors outline the mathematical modeling of antenna look angles for a satellite ground control station. The model uses mathematical equations to express these angles. [4] provides a model for the azimuth and elevation angles with validation and analysis. The two studies [3] and [4] focus on calculating the look angles of the VSAT antenna at the ground station but do not address the polarization of the satellite

signals. They concentrate on the geometric aspect of antenna positioning without considering the signal polarization requirements for optimal communication. [5] introduce approaches for VSAT control with open loop and closed loop methods. The open-loop method utilizes the satellite's known position and look angles to adjust the antenna's orientation based on its current attitude. The closed-loop method improves accuracy by continuously adjusting the antenna's orientation to maximize the receiver signal strength. This feedback-driven approach ensures that the antenna maintains the optimal position relative to the satellite. However, this necessitates the mechanical scanning of the antenna across the sky, which can be complex and time-consuming. A third approach can be a hybrid of the two abovementioned methods. In [5], PID control law is applied. This PID controller uses look angles as a reference. Data from the IMU sensor is used to calculate the current attitude of the antenna. In [6], the analysis of angular velocities and accelerations in both time and frequency domains is conducted to establish the typical design requirements for tracking antenna systems. Meanwhile, [7] provides details on satellite look angles, which are essential for orienting mobile satellite tracking antennas to either GEO (Geostationary Earth Orbit) or non-GEO communication satellites.

The attitude of a VSAT antenna mounted on a ship constantly changes in tandem with the ship's hull movements. To maintain a stable satellite connection, the VSAT system calculates the ship's orientation and adjusts the antenna's position to track the specified look angles. This study introduces a method to calculate the ship's attitude angles and suggests an approach for determining the rotation angles required around non-orthogonal axes to maintain the antenna's directional stability and polarization alignment. The ship's attitude angles describe its orientation within the navigation coordinate system. The rotation angles serve as reference inputs required by the satellite-tracking antenna controller. The rest of the paper is divided into 3 parts. Section 2 presents the VSAT system with a non-orthogonal axis system and the method to determine the look angle stability parameters. Section 3 presents the simulation test results. Section 4 is the conclusion.

2. METHODOLOGY

2.1. VSAT system model with a non-orthogonal motion axes

In this model, the VSAT antenna rotates around 3 non-orthogonal axes: the azimuth axis, the R axis, and the P axis (figure 1). Let select the coordinate system $O_A X_A Y_A Z_A$ (Frame 1) fixing to the ship's deck. The coordinate system $O_R X_R Y_R Z_R$ (Frame 2) is attached to the base of the axis R. The coordinate system $O_P X_P Y_P Z_P$ (Frame 3) is mounted to the base of the axis P. To utilize the transformation formula for continuous rotation chain, additional rotations around the Y_{A1} and Y_{R1} axes (figure 1). In the initial conditions, we assume that the Y_A , Y_R , and Y_P axes have the same direction (lateral direction). The transformation from frame 1 to frame 2 is performed via two rotations: the rotation around the Z_A axis at an angle α transforms $O_A X_A Y_A Z_A$ to a new frame $O_{A1} X_{A1} Y_{A1} Z_{A1}$ and the rotation around the Y_{A1} axis at the fixed angle κ transforms $O_{A1} X_{A1} Y_{A1} Z_{A1}$ to $O_R X_R Y_R Z_R$. The transformation matrix from the frame 1 to the frame 2 is: $\mathbf{R}_1^2 = \mathbf{R}_Y^T(\kappa)\mathbf{R}_Z^T(\alpha)$ [9]. Where $\mathbf{R}_{X_i}(\alpha_i)$ - Rotation matrix around the axis X_i at the angle α_i [8]. For the transformation from frame 2 to frame 3, we execute two consecutive rotations. One of the rotations is performed around the Z_R axis by a specified angle β , which transforms the system $O_R X_R Y_R Z_R$ to $O_{R1} X_{R1} Y_{R1} Z_{R1}$. The second rotates the system $O_{R1} X_{R1} Y_{R1} Z_{R1}$ around the Y_{R1} axis at the particular angle of σ . The transformation matrix from the system 2 to 3 is: $\mathbf{R}_2^3 = \mathbf{R}_Y^T(\sigma)\mathbf{R}_Z^T(\beta)$ [9]. Figure 2 illustrates the chain of rotations in this non-orthogonal VSAT model. While rotations around the Azimuth and R axes are responsible for directing the VSAT antenna towards the satellite, the rotation around the P axis does not affect the antenna's orientation. Instead, it adjusts the polarization skew, ensuring the correct alignment for optimal signal reception and transmission. In frame 3, we denote \vec{k} as a unit vector of axis P. It's coordinates in the frame 3: $\vec{k}_P = [0 \ 0 \ 1]^T$.

When the antenna is aligned with the satellite, the vector \vec{k} is directed towards the satellite.

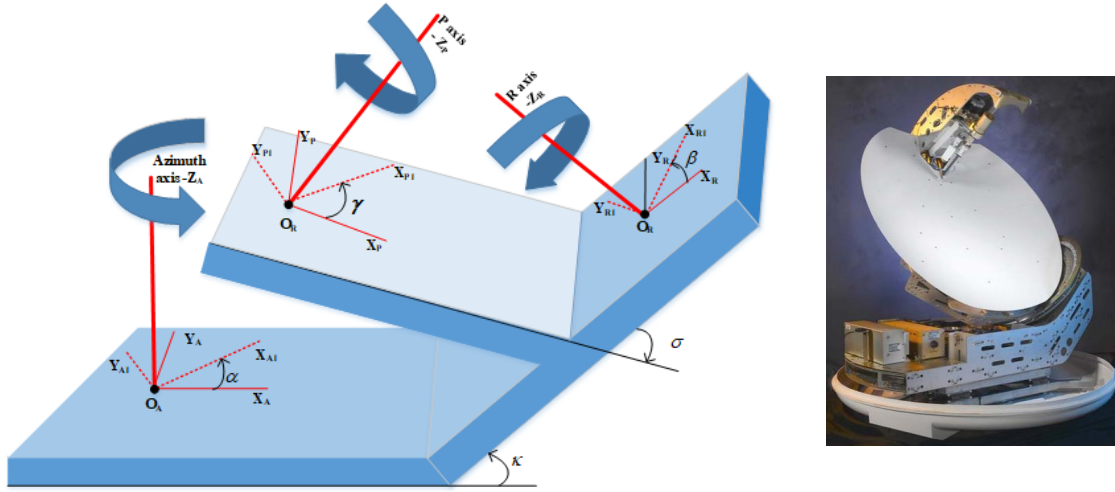


Figure 1. A VSAT system with non-orthogonal axes.

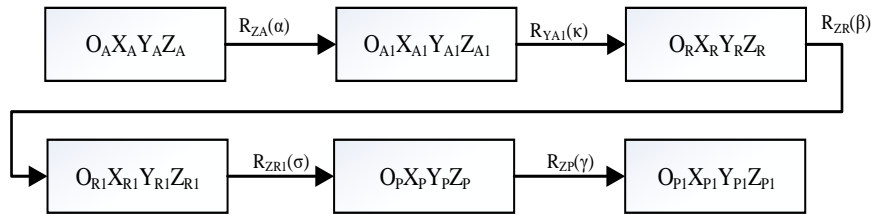


Figure 2. The chain of rotations in the non-orthogonal VSAT model.

2.2. Determination of the look-angle stabilization parameters

2.2.1. Calculation of azimuth, elevation, and rotation control angles α , β around Azimuth and R axes

First, we determine the direction vector \vec{N} from the antenna to the registered geostationary satellite. In the body coordinate (the frame 1), according to [13]:

$$\vec{N}^B = [X_B \ Y_B \ Z_B]^T = \mathbf{C}_N^B \mathbf{C}_E^N [X_B \ Y_B \ Z_B]^T \quad (1)$$

Where: \mathbf{C}_N^B – The transformation matrix from the navigation system (ENU) to the body frame fixed to the ship's hull:

$$\mathbf{C}_N^B = \mathbf{R}_x^T(\phi) \mathbf{R}_y^T(\theta) \mathbf{R}_z^T(\psi) = \begin{bmatrix} c_\theta c_\psi & c_\theta s_\psi & -s_\theta \\ s_\phi s_\theta c_\psi - c_\phi s_\psi & s_\phi s_\theta s_\psi + c_\phi c_\psi & s_\phi c_\theta \\ c_\phi s_\theta c_\psi + s_\phi s_\psi & c_\phi s_\theta s_\psi - s_\phi c_\psi & c_\phi c_\theta \end{bmatrix},$$

here, ϕ, θ, ψ are Roll, Pitch, and Yaw respectively, in the ENU (East, North, Up) coordinate system; these angles are mentioned in 2.2.3; \mathbf{C}_E^N - The transformation matrix from the Earth-fixed coordinate system (E-frame) to the navigation system (N-frame):

$$\mathbf{C}_E^N = \begin{bmatrix} -s_{\lambda_p} & c_{\lambda_p} & 0 \\ -s_{\phi_p} c_{\lambda_p} & -s_{\phi_p} s_{\lambda_p} & c_{\phi_p} \\ c_{\phi_p} c_{\lambda_p} & c_{\phi_p} s_{\lambda_p} & s_{\phi_p} \end{bmatrix}; \quad \begin{bmatrix} X_E \\ Y_E \\ Z_E \end{bmatrix} = \begin{bmatrix} (R + h_s) c_{\phi_s} c_{\lambda_s} \\ (R + h_s) c_{\phi_s} s_{\lambda_s} \\ (R + h_s) s_{\phi_s} \end{bmatrix} - \begin{bmatrix} (R + h_p) c_{\phi_p} c_{\lambda_p} \\ (R + h_p) c_{\phi_p} s_{\lambda_p} \\ (R + h_p) s_{\phi_p} \end{bmatrix}$$

Here, R is the radius of the Earth; λ_p, ϕ_p, h_p are respectively the longitude, latitude, and altitude of the station VSAT. These parameters can be obtained using a GPS devices; λ_s, ϕ_s, h_s are respectively the longitude, latitude, and altitude of the registered geostationary satellite. Here, we

denote $s_{\lambda_p} = \sin(\lambda_p)$; $c_{\lambda_p} = \cos(\lambda_p)$; $\bar{\mathbf{n}}^B = \bar{\mathbf{N}}^B / \|\bar{\mathbf{N}}^B\| = [n_1 \ n_2 \ n_3]^T$. The normalization of the vector $\bar{\mathbf{N}}^B$. The elevation and azimuth angles of the VSAT antenna in the body frame (the system 1) after stabilizing the direction of the VSAT antenna are:

$$\varepsilon = \text{asin}(n_3 / \sqrt{n_1^2 + n_2^2 + n_3^2}) = \text{asin}(n_3); \quad \mathcal{U} = \text{atan2}(n_1, n_2) \quad (2)$$

The problem now is transforming the vector $\vec{\mathbf{k}}$ (in 2.1) to the vector $\vec{\mathbf{n}}$ via two sequential rotations around the axes R and Azimuth. In the rotation around the axis R, we try to move the vector $\vec{\mathbf{k}}$ to the new position inclined to the ship's deck plane at an angle ε . In the coordinate system $O_{A1}X_{A1}Y_{A1}Z_{A1}$ the vector $\vec{\mathbf{k}}$ after rotating around the axis R is:

$$\bar{\mathbf{k}}_{A1} = \mathbf{R}_Y(\kappa)\mathbf{R}_Z(\beta)\mathbf{R}_Y(\sigma)\bar{\mathbf{k}}_P = \begin{bmatrix} c_\kappa & 0 & s_\kappa \\ 0 & 1 & 0 \\ -s_\kappa & 0 & c_\kappa \end{bmatrix} \begin{bmatrix} c_\beta & -s_\beta & 0 \\ s_\beta & c_\beta & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_\sigma & 0 & s_\sigma \\ 0 & 1 & 0 \\ -s_\sigma & 0 & c_\sigma \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} c_\kappa s_\sigma c_\beta + s_\kappa c_\sigma & c_\kappa s_\sigma c_\beta + s_\kappa c_\sigma & -s_\kappa s_\sigma c_\beta + c_\kappa c_\sigma \end{bmatrix}^T \quad (3)$$

To get β , we solve the equation (4):

$$\sin\varepsilon = -s_\kappa s_\sigma c_\beta + c_\kappa c_\sigma = n_3 \quad (4)$$

Two solutions β_1, β_2 are:

$$\beta_1 = \text{acos}\left(\frac{c_\kappa c_\sigma - n_3}{s_\kappa s_\sigma}\right); \quad \beta_2 = -\text{acos}\left(\frac{c_\kappa c_\sigma - n_3}{s_\kappa s_\sigma}\right) \quad (5)$$

Next, we define a rotation angle α around the Azimuth axis to move the vector $\vec{\mathbf{k}}$ to the vector $\vec{\mathbf{n}}$. Let $\mathbf{R}_{X_A Y_A} = \begin{bmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{bmatrix}$. The rotation angle α is the solution of the equation (6):

$$\begin{bmatrix} c_\kappa s_\sigma c_\beta + s_\kappa c_\sigma \\ s_\sigma s_\beta \end{bmatrix} = \mathbf{R}_{X_A Y_A}^T \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} = \begin{bmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{bmatrix} \begin{bmatrix} n_1 \\ n_2 \end{bmatrix} \quad (6)$$

Solving the equation (6), we have two solutions α_1, α_2 corresponding to $\beta = \beta_1, \beta = \beta_2$:

$$\begin{aligned} \alpha_1 &= \text{atan2}[n_2(c_\kappa s_\sigma c_{\beta_1} + s_\kappa c_\sigma) - n_1 s_\sigma s_{\beta_1}, n_1(c_\kappa s_\sigma c_{\beta_1} + s_\kappa c_\sigma) + n_2 s_\sigma s_{\beta_1}]; \\ \alpha_2 &= \text{atan2}[n_2(c_\kappa s_\sigma c_{\beta_2} + s_\kappa c_\sigma) - n_1 s_\sigma s_{\beta_2}, n_1(c_\kappa s_\sigma c_{\beta_2} + s_\kappa c_\sigma) + n_2 s_\sigma s_{\beta_2}] \end{aligned} \quad (7)$$

2.2.2. Determination of the rotation angle γ to stabilize polarization

In the ENU coordinate system, the vector representing polarization of the satellite signal remains unchanged. After obtaining the antenna orientation, we perform a rotation around the P axis to obtain polarization and stabilize it during satellite tracking control. We suppose that at time $t = 0$ ($\alpha = \alpha_0, \beta = \beta_0, \gamma = 0$), the VSAT system gets its necessary direction and polarization. Select any vector $\vec{\mathbf{p}}_0$, that is not parallel to the vector $\vec{\mathbf{n}}$. The vector $\vec{\mathbf{p}}_0$ can be chosen as $\vec{\mathbf{p}}_0^N = \mathbf{C}_{B|t=0}^N \mathbf{R}_Z(\alpha_0)\mathbf{R}_Y(\kappa)\mathbf{R}_Z(\beta_0)\mathbf{R}_Y(\sigma)\bar{\mathbf{e}}_{X_P}$. Here, $\bar{\mathbf{e}}_{X_P} = [1 \ 0 \ 0]^T$ - the coordinate of the unit vector of the axis X_P represented in the coordinate system $O_P X_P Y_P Z_P$. At time t , we suppose that the direction of the antenna is stabilized at $\alpha = \alpha_t, \beta = \beta_t, \gamma = \gamma_t$. Then, the vector $\vec{\mathbf{p}}_0$ rotates to a new position $\vec{\mathbf{p}}_t$, which has coordinates in the navigation coordinate system as: $\vec{\mathbf{p}}_t^N = \mathbf{C}_{B|t}^N \mathbf{R}_Z(\alpha_t)\mathbf{R}_Y(\kappa)\mathbf{R}_Z(\beta_t)\mathbf{R}_Y(\sigma)\bar{\mathbf{e}}_{X_P}$. Let $\vec{\mathbf{p}}_{0|\perp\vec{\mathbf{n}}}, \vec{\mathbf{p}}_{t|\perp\vec{\mathbf{n}}}$ are respectively the perpendicular components of the vector $\vec{\mathbf{p}}_0, \vec{\mathbf{p}}_t$ projected onto the vector $\vec{\mathbf{n}}$. We have: $\vec{\mathbf{p}}_{0|\perp\vec{\mathbf{n}}} = \vec{\mathbf{p}}_0 - (\vec{\mathbf{p}}_0, \vec{\mathbf{n}})\vec{\mathbf{n}}$; $\vec{\mathbf{p}}_{t|\perp\vec{\mathbf{n}}} = \vec{\mathbf{p}}_t - (\vec{\mathbf{p}}_t, \vec{\mathbf{n}})\vec{\mathbf{n}}$. The angle γ_t of rotation around the P axis is determined by the expression (8). By rotating around the axis P, the VSAT antenna get it's polarization.

$$\gamma_t = \angle(\vec{\mathbf{p}}_{0|\perp\vec{\mathbf{n}}}, \vec{\mathbf{p}}_{t|\perp\vec{\mathbf{n}}}) = \text{sign}[(\vec{\mathbf{p}}_{0|\perp\vec{\mathbf{n}}} \times \vec{\mathbf{p}}_{t|\perp\vec{\mathbf{n}}}) \cdot \vec{\mathbf{n}}] \text{acos}((\vec{\mathbf{p}}_{0|\perp\vec{\mathbf{n}}}, \vec{\mathbf{p}}_{t|\perp\vec{\mathbf{n}}}) / \|\vec{\mathbf{p}}_{0|\perp\vec{\mathbf{n}}}\| \|\vec{\mathbf{p}}_{t|\perp\vec{\mathbf{n}}}\|) \quad (8)$$

2.2.3. Determination of the ship's attitude angles in the ENU coordinate system

There are numerous methods for determining a ship's attitude angle. In this paper, we use an inertial measurement unit (IMU), an inclinometer, a compass, and a Kalman filter for our solution.

Data from the IMU sensor is used to determine the pre-estimated attitude angles. These pre-estimated angles are calculated based on the kinematic equation (9) [8]. Here: ψ, θ, ϕ - Yaw, pitch, roll of the ship's hull; p, q, r angular velocities from the IMU sensor.

$$\begin{bmatrix} \dot{\psi} \\ \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} 0 & s_\phi/c_\theta & c_\phi/c_\theta \\ 0 & c_\phi & -s_\phi \\ 1 & s_\phi t_\theta & c_\phi t_\theta \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix} \quad (9)$$

By discrete integration [9], we can get pre-estimate attitude angles $\psi_k^-, \theta_k^-, \phi_k^-$.

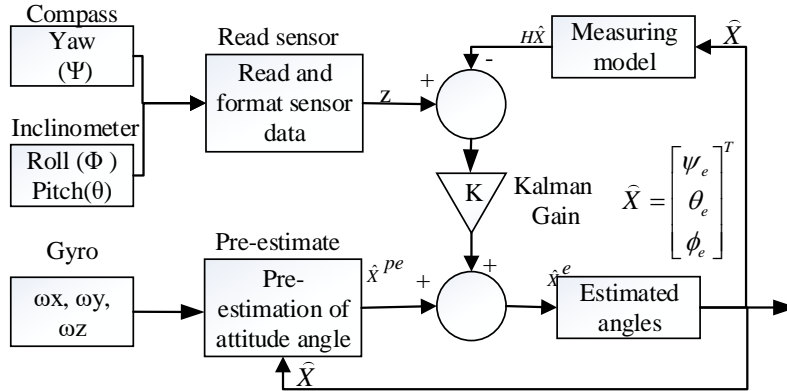


Figure 3. Block diagram of attitude angle estimation.

Let state vector: $\mathbf{x} = [\psi \ \theta \ \phi \ e_p \ e_q \ e_r]^T$. Here e_p, e_q, e_r - Angular velocity errors. Let $\delta \mathbf{x} = [\delta\psi \ \delta\theta \ \delta\phi \ \delta e_p, \delta e_q, \delta e_r]^T$. The evolution of for $\delta \mathbf{x}$ is given as: $\delta \mathbf{x} = \mathbf{F}\delta \mathbf{x} + \mathbf{G}w$. Where w - Represents the wideband measurement errors on the $p, q,$ and r gyro outputs and driving noise terms for the stochastic gyro biases, w is characterized by the power spectral density matrix \mathbf{Q} . Let measurement output $\mathbf{z} = [\psi_{com} \ \theta_{com} \ \phi_{inc}]$ achieving from the compass and inclinometer sensors. The measurement model is: $\mathbf{z} = \mathbf{H}\mathbf{x}$. Where \mathbf{H} - The measurement matrix. Let \mathbf{R} - The measurement noise covariance matrix. Applying the Kalman filter for the discrete model, we have the Kalman gain [10]:

$$\mathbf{K}_k = \mathbf{P}_k^- \mathbf{H}^T (\mathbf{H}^T \mathbf{P}_k^- \mathbf{H} + \mathbf{R}) \quad (10)$$

Where: $\mathbf{P}_k^- = \mathbf{F}_{k-1} \mathbf{P}_{k-1}^- \mathbf{F}_{k-1}^T + \mathbf{G}_{k-1} \mathbf{Q}_{k-1} \mathbf{G}_{k-1}^T$; $\mathbf{P}_k^+ = (\mathbf{I}_{6 \times 6} - \mathbf{K}_k \mathbf{H}) \mathbf{P}_k^-$. The estimation of the error state vector is calculated by (11):

$$\delta \mathbf{x}_k^+ = \mathbf{K}_k (\mathbf{z}_k - \mathbf{H} \mathbf{x}_k^-) \quad (11)$$

The estimations of attitude angles (yaw, pitch, roll) are:

$$\hat{\psi}_k^+ = \psi_k^- + \delta x_k^+[1], \theta_k^- = \theta_k^- + \delta x_k^+[2], \phi_k^- = \phi_k^- + \delta x_k^+[3] \quad (12)$$

In this paper, the author does not delve into the algorithm in detail but plans to provide a more comprehensive explanation in future research.

3. RESULTS AND DISCUSSION

3.1. Test attitude angle measuring block

The authors developed an IMU-VN block to measure attitude angles (figure 4). We also performed tests on an oscillation system. This system uses 17-bit encoder (equivalent to the resolution of 0.003°) to encode the position. The test results are shown in table 1. RMS errors between the attitude angles returned from the IMU-VN block and the reference angles

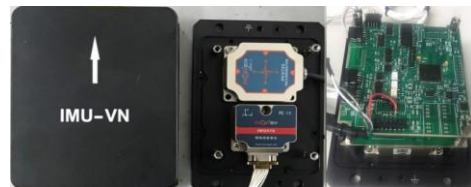


Figure 4. Attitude angle measuring block.

inferred from encoder values are respectively $\delta_{yaw} = 0.01^\circ$, $\delta_{pitch,roll} = 0.08^\circ$ for yaw and pitch (roll) angles.

Table 1. Test results with the attitude angle measuring block IMU-VN.

TT	yaw			Pitch		
	Ref. Yaw (°)	Yaw (°)	Deviation (°)	Ref. Pitch (°)	Pitch (°)	Deviation (°)
1	-19.75176	-19.63136	0.1204	-11.75176	-11.63136	0.1204
2	-5.03855	-5.13663	-0.09808	-5.53855	-5.63663	-0.09808
3	5.04129	5.03486	-0.00643	-1.04129	-0.93486	0.10643
4	12.74162	12.97658	0.23496	11.94162	11.97658	0.03496
5	22.4019	22.3819	-0.02	22.9019	22.9819	0.08
6	27.39974	27.2804	-0.11934	25.39974	25.4804	0.08066
7	17.99254	17.95061	-0.04193	16.99254	16.95061	-0.04193
8	9.67458	9.71773	0.04315	3.87458	3.81773	-0.05685
9	-10.78015	-10.6812	0.0989	-10.78015	-10.6512	-0.1289
RMS of IMU-VN	0.10°			0.08°		
RMS of ORSAT AL7103	0.10°			0.10°		

These results meet the requirement for RMS error of the attitude angle measurement block of the ORSAT AL7103, ensuring it does not exceed 0.1°.

3.2. Simulation for calculation of angular stability parameters

First, we evaluate the influence of VSAT station location on the change of look-angle parameters. For convenience of evaluation, we assume that the body coordinate system coincides with the navigation coordinate system ($\phi = 0, \theta = 0, \psi = 0$). Let $\kappa = -45^\circ$, $\sigma = 45^\circ$. The satellite has longitude, latitude, and altitude, respectively: $\lambda_s = 131.8$, $\varphi_s = 0.02$, $h_s = 42200$ km. The radius of the earth is $R = 6371$ km. Calculation results are shown in table 2.

Table 2. Simulation results with the carrier ship not changing the attitude angle.

TT	latitude (°)	longitude (°)	altitude (km)	ζ (°)	ξ (°)	α (°)	β (°)
VSAT1($\varphi_p, \lambda_p, h_p$)	16.1191	108.3364	0	122.6340	57.8420	139.4115 -74.2349	46.1853 -46.1853
VSAT2($\varphi_p, \lambda_p, h_p$)	16.1230	108.2123	0	122.4863	57.7265	139.3293 -74.4479	46.3559 -46.3559
VSAT3($\varphi_p, \lambda_p, h_p$)	16.1195	108.3370	0	122.6353	57.8423	139.4127 -74.2334	46.1849 -46.1849
VSAT2-VSAT1	Distance = 13.264 km			-0.1477	-0.1155	-0.0822 -0.213	0.1706 -0.1706
VSAT3-VSAT2	Distance =13.326 km			0.149	0.1158	0.0834 0.2145	-0.171 0.171

It is evident that, given the considerable 13 km separation between VSAT station locations, the angular changes in azimuth and elevation, as well as the rotational displacements around the Azimuth and R axes, are tiny, remaining under 0.2°. This indicates that the ship's hull orientation significantly affects the antenna's ability to maintain proper alignment.

In the subsequent simulation, we modify the ship's attitude angles (roll, pitch, and yaw) to observe how they influence the elevation and azimuth angles of the antenna. Additionally, we analyze the

rotation angles required to maintain proper direction and polarization for the VSAT antenna. The ship's attitude angles are changed harmoniously with a period of 6 seconds, as shown in the figures. The amplitudes of roll, pitch, and yaw are 30° , 20° , 6° , respectively. The oscillations of the azimuth and elevation angles, along with the stabilization rotation angles for antenna alignment, correspond directly to the frequency of changes in the roll, pitch, and yaw of the ship's hull.

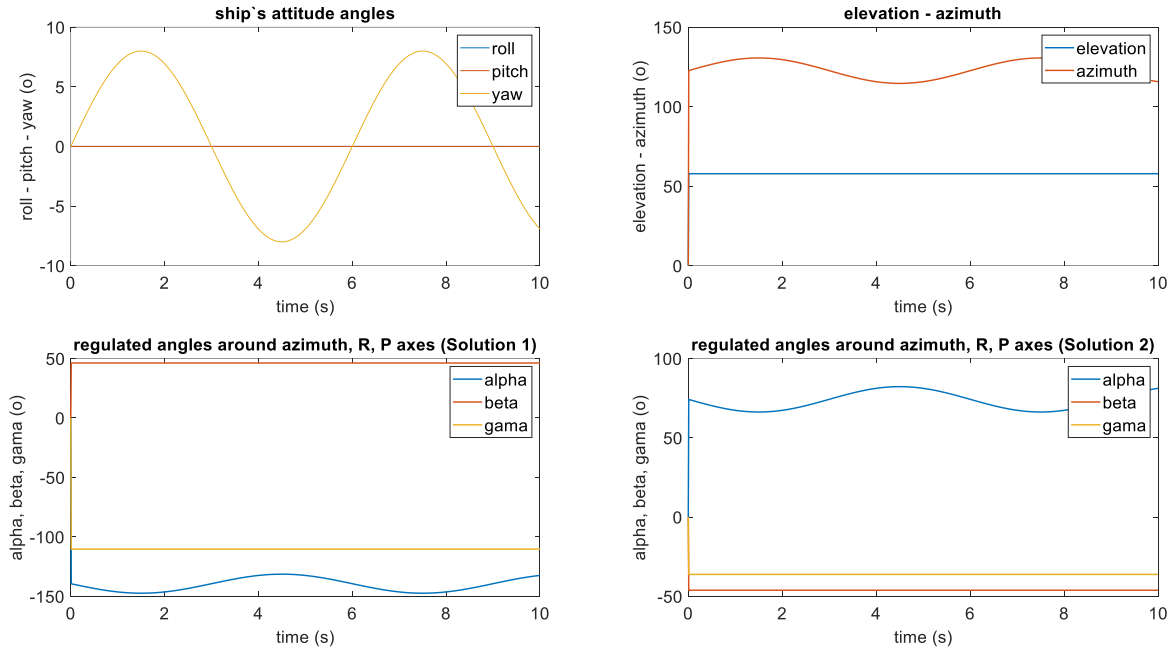


Figure 5. Experiment with varying Yaw angles.

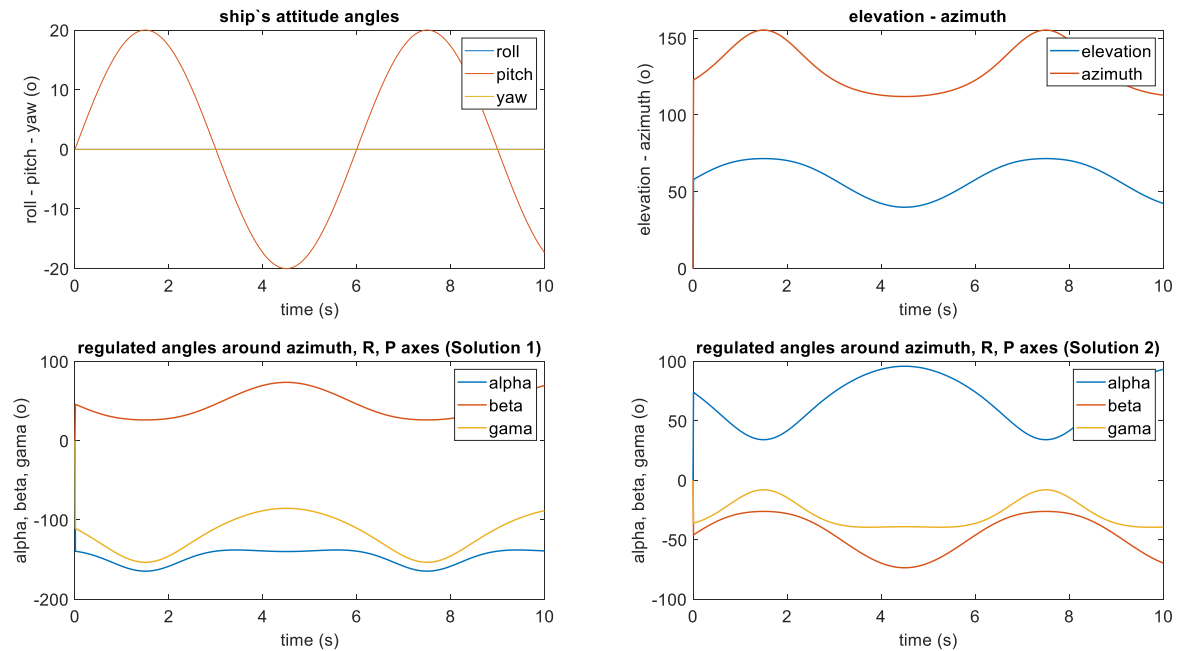
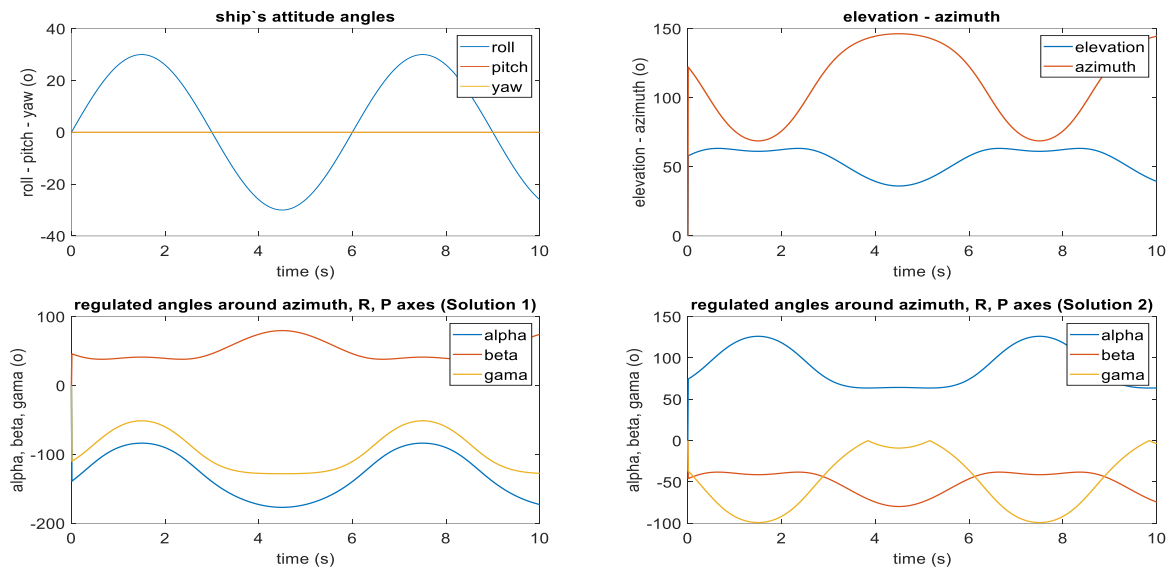


Figure 6. Experiment with varying Pitch angles.



Hình 7. Experiment with varying Roll angles.

When the ship experiences changes in its yaw angle (figure 5), only the azimuth angle of the antenna is affected, requiring adjustment solely around the Azimuth axis for stabilization. In other scenarios (figures 6, 7), changes in the pitch or roll will alter both the azimuth and elevation angles of the antenna. In these cases, to stabilize the antenna's orientation and polarization, control across all three axes of the VSAT system is necessary.

4. CONCLUSIONS

The paper introduces a method for calculating look-angle stability parameters for antennas in a non-orthogonal axis VSAT system. This approach allows for the determination of azimuth, elevation, and rotation angles around the system's non-orthogonal axes. Additionally, it proposes a solution for estimating the ship's attitude. These parameters are essential for directing the VSAT antenna toward the communication satellite while ensuring the correct polarization. Simulation results highlight the significant impact of the ship's attitude on VSAT antenna stability, whereas the ship's position has a comparatively minor effect on the change of antenna's orientation. Harmonic changes in the ship's roll, pitch, yaw cause changes in the look-angle stability parameters at the same frequency. For the developed attitude angle measurement block (IMU-VN), the RMS errors for yaw and pitch were measured at 0.1° and 0.08° , respectively. These values below the specified requirements for the ORSAT AL7103 system.

REFERENCES

- [1]. Pratt, Timothy, and Jeremy E. Allnut. "Satellite communications". John Wiley & Sons, (2019).
- [2]. Debruin, James. "Control systems for mobile satcom antennas." IEEE Control Systems Magazine 28.1: 86-101, (2008).
- [3]. Ayansola, Ogundele Daniel, ECA Akoma Henry, and A. Adediran Yinusa. "Mathematical modelling of antenna look angles of geostationary communications satellite using two models of control stations." 2010 3rd International Conference on Advanced Computer Theory and Engineering (ICACTE). Vol. 4. IEEE, (2010).
- [4]. Ogundele, Daniel Ayansola, et al. "Model validation and analysis of antenna look angles of geostationary satellite." 2012 IEEE International Conference on Computer Science and Automation Engineering (CSAE). Vol. 2. IEEE, (2012).
- [5]. Kumar, Sachin, and Nitin Gupta. "Satcom on the move (SOTM) system."

- [6]. Lorenz, Mario, Markus Mehnert, and Albert Heuberger. "Measurements of mechanical disturbances of vehicle mounted, mobile very small aperture terminals (vsat)." Proceedings of the 11th Workshop Digital Broadcasting. (2010).
- [7]. Ilcev, St D. "Satellite look angles, track and geometry in mobile satellite communications." 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT). IEEE, (2016).
- [8]. Henderson, David M. "Euler angles, quaternions, and transformation matrices for space shuttle analysis". No. DN-1.4-8-020. (1977).
- [9]. Weisstein, Eric W. "Rotation matrix." <https://mathworld.wolfram.com/> (2003).
- [10]. Franklin, Gene F., J. David Powell, and Michael L. Workman. "Digital control of dynamic systems". Vol. 3. Menlo Park: Addison-wesley, (1998).

TÓM TẮT

Xác định tham số ổn định góc nhìn cho hệ thống điều khiển ăng ten VSAT lắp trên tàu biển với hệ trục chuyển động không trục giao

Truyền thông VSAT phụ thuộc vào nhiều yếu tố, chẳng hạn như cường độ tín hiệu, độ nhạy của máy thu và các yếu tố nhiễu môi trường. Để đảm bảo chất lượng tín hiệu tối ưu, ăng-ten VSAT phải được căn chỉnh và phân cực đúng cách về phía vệ tinh. Đối với hệ thống VSAT được lắp đặt trên tàu, nhiễu từ sóng, gió và dòng chảy làm gián đoạn đáng kể khả năng duy trì hướng ổn định của ăng-ten về phía mục tiêu vệ tinh. Để tăng cường hiệu quả về mặt cấu trúc, độ chính xác chuyển động và độ cứng, một số hệ thống VSAT trên tàu, chẳng hạn như ORSAT AL7103 và AL7107, kết hợp các thiết kế có trục chuyển động không vuông góc. Bài viết giới thiệu phương pháp tính toán các thông số ổn định góc nhìn cho loại hệ thống VSAT này, bao gồm góc phương vị và góc độ cao, góc điều khiển quay và góc tư thế của tàu. Một số kết quả thí nghiệm và mô phỏng chứng minh tính khả thi của phương pháp được đề xuất.

Từ khoá: Ổn định góc nhìn; Phân cực; Bám vệ tinh; Liên lạc vệ tinh.